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OPERATIONAL CHARACTERISTICS OF THE WATERMARK MODEL 200 SOIL WATER POTENTIAL SENSOR FOR IRRIGATION MANAGEMENT

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Operational Characteristics of the Watermark Model 200 Soil Water Potential Sensor for Irrigation Management

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Abstract

The static and dynamic response characteristics of the Watermark model 200 soil water potential sensor were evaluated using the pressure plate method and greenhouse experiments. The sensor had a nearly linear resistance versus water potential relationship within the 0 to −200 kPa (0 to −29 psi) range. At saturation, sensor resistance was approximately 1 kΩ, and at −103 kPa (−15 psi) resistance was approximately 23 kΩ, with a coefficient of variation of 11% (49 sensors). Using three to six sensors at each location and depth should yield estimates of soil water potential within 10% of the actual value with a 90% confidence level. The dynamic response was good during typical soil water drying cycles following complete rewetting, but the sensors did not respond fully to rapid drying or partial rewetting of the soil. Response was improved, without affecting the basic calibration, when a finer textured material with greater unsaturated hydraulic conductivity was used in the transmission portion of the sensor. **Keywords.** Sensors, Water management, Irrigation.

Introduction

Irrigated agriculture is the single major user of water in semi-arid and arid regions. Increasing population, drought, and concern about water and energy supplies and environmental quality have increased the pressure on irrigated agriculture to better manage and conserve water. At the farm level, production and profitability can be greatly affected by irrigation management, particularly for high value, drought sensitive and shallow rooted crops such as potato.

An important component of good irrigation management is measurement of soil water content or potential over space and time. An ideal soil water sensor would respond instantaneously to changes in soil water content or potential, and would be inexpensive, reliable, maintenance free, accurate within the needed range, and produce an electrical signal suitable for electronic measurement, analysis, and control.

Currently available sensors include the tensiometer, the neutron probe, thermal flux devices, and electrical resistance devices, none of which are well suited for practical applications for reasons such as cost or maintenance requirements. Of the available sensors, electrical resistance devices, such as gypsum blocks, have certain desirable qualities (low cost and low maintenance), but lack sufficient accuracy in the 0 to −100 kPa (−15 psi) soil water potential range, which is required for profitable production of many crops. The Watermark Model 200 sensor is an electrical resistance device which the manufacturer (Irrometer Company, Inc., P.O. Box 2424, Riverside, CA 92516) claims addresses this problem.

Electrical resistance devices consist of electrodes embedded in a porous matrix. The soil solution, commonly buffered with gypsum to reduce sensitivity to soil water salinity, provides a path for electrical conduction. The sensor is in hydraulic contact with the soil solution, which it absorbs or releases in response to matric potential gradients, ideally until equilibrium is reached. Electrically, the sensor consists of a relatively conductive liquid interspersed within virtually non-conductive solid and gaseous phases. The resistance of the sensor is therefore a function of the liquid content, which in turn is a function of soil water potential. To avoid polarization at the electrodes, an alternating current excitation is generally used to measure the resistance.

In traditional gypsum blocks the entire porous matrix is a solid gypsum-based material, while in Watermark sensors the matrix is a loose graded sand material. This material is held in place by the outside case of the sensor, and a solid gypsum-based wafer divides the matrix material into a transmission section and a measurement section (fig. 1). In the transmission section, the case has holes and the matrix is held within the case by a permeable synthetic membrane. Soil water enters this section through the holes and membrane, passes through the gypsum wafer which provides salinity buffering, and enters the measurement section.

In addition to sensor resistance at steady-state soil water potentials, the dynamic response to typical wetting and drying cycles that occur under irrigation is very important. If the sensor can not respond rapidly enough, the measurements made with it will lag behind actual soil water content. For example, during a drying cycle a sensor with a slow response rate will indicate that the soil is wetter than it actually is. In the Watermark sensor, the measurement section is isolated from the soil, and so a finite amount of water must move from the soil, through the transmission section and into the measurement section

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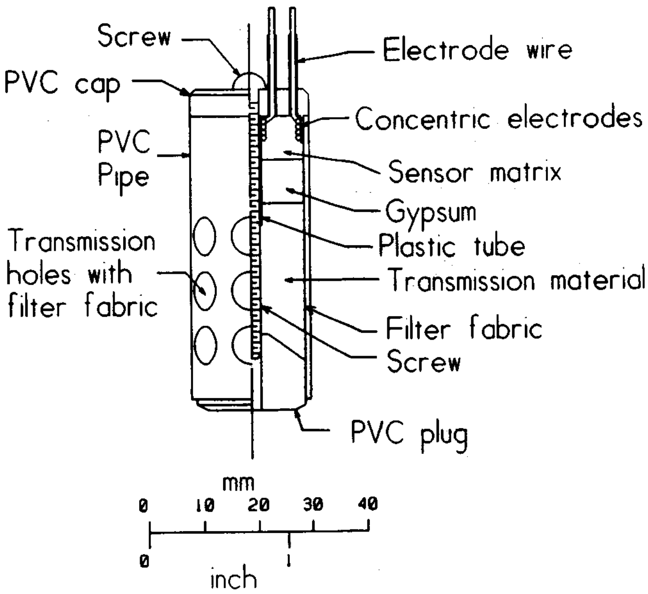

Figure 1–Construction details of the Watermark sensor.

in order for the sensor to respond to changes in soil water potential. The time required for this water movement is a function of potential gradients and hydraulic conductivity within the soil and the sensor. The sensor's usefulness for real time measurement of soil water potential would be limited if the resulting response time is long relative to typical rates of change in soil water potential.

Thomson and Armstrong (1987) presented an equation relating Watermark sensor resistance to soil water potential and temperature, of the form:

$$R = \left\{\alpha - \left[\frac{\beta}{(1+\sigma S)}\right]\right\}\left(\delta - T + kT^2\right) \qquad (1)$$

where
 R = sensor resistance (KΩ),
 S = soil water potential (– kPa),
 T = temperature (° C),
and α, β, σ, δ, and k were statistically determined to have values of:
 α = 1.062,
 β = 1.062,
 σ = 0.01306,
 δ = 34.214,
 k = 0.01060.

Thomson and Armstrong (1987) developed equation 1 from measurements of three sensors in a temperature controlled pressure plate extractor, for temperatures between 4° C and 38° C (39° F to 100° F), and pressures from 10 kPa to 100 kPa (1.5 to 15 psi). The measurement circuit consisted of an 1100 hz sinewave oscillator to provide ac excitation, a sensor signal amplifier, and a rectifier/filter stage.

Wang and McCann (1988) presented a linear calibration equation for Watermark sensors, and Wang (1988) subsequently developed an equation of the form:

$$R = \alpha\left[\frac{S}{\beta}\right]^{a}\left[1 + k(18 - T)\right] \qquad (2)$$

where
 R = sensor resistance (kΩ),
 S = soil water potential (– kPa),
 T = temperature (° C),
and α, β, a, and k were statistically determined to have values of:
 α = 0.93,
 β = 2.1,
 a = 0.8,
 k = 0.03.

In equation 2, the electrical conductance (l/R) of the sensor is assumed to be directly proportional to its liquid content. The relationship between conductance and soil water potential is modeled after the Brooks-Corey equation, which relates soil water content to soil water potential (Brooks and Corey, 1966). Using this form of equation, conductivity is analogous to soil water content.

The effect of temperature in equation 2 is linear within the range of 14° C to 26° C (57° F to 79° F), which is typical of field conditions in Idaho during the growing season. Similar to Thomson and Armstrong (1987), the parameters in equation 2 were developed using data from a number of sensors in a temperature controlled pressure plate extractor. Measurements were made using a Campbell Scientific CR21 data logger operating in manual mode.

Both Thomson and Armstrong (1987) and Wang (1988) indicated that Watermark sensors performed well, but equations 1 and 2 yield substantially different results. In equation 2, sensor resistance is substantially larger at a given soil water potential and temperature than in equation 1. In terms of the temperature effect, both equations are consistent and indicate a change in resistance of approximately 2.8% to 3.3% per °C (1.6% to 1.8% per ° F) between 14° C and 28° C (57° F and 82° F).

An important consideration in using such sensors is the variability between individual sensors. The degree of confidence in a measurement may be increased by using the average reading of a number of sensors rather than the reading from a single sensor, assuming identical soil water potential for each sensor. Wang (1988) showed that the variance in resistance of the sample of sensors he used increased with increasing dryness. The coefficient of variation however was reasonably constant, ranging from 2.5% at −34 kPa (−4.9 psi) to 1.8% at −103 kPa (−14.7 psi). Thus, the absolute error in measuring soil water potential is greater in dryer soils but the error relative to the mean is approximately the same for the range of soil water potential under consideration. The corresponding errors in estimations of soil water content are, of course, dependent on the soil water content/soil water potential relationship for the particular soil.

We conducted additional evaluations of static response and sensor variability in a pressure-plate apparatus under constant temperature conditions. We also evaluated dynamic response to changes in soil water potential, such as typically occur in soils as a result of soil water depletion by evapotranspiration and soil water addition from irrigation and precipitation. In addition, we modified a small number of sensors to evaluate the effect of different transmission section matrix materials on response time.

Methods and Materials

Static Response

The static response of the sensors to soil water potential was measured using a pressure plate apparatus in a temperature controlled environment. A 200 kPa (30 psi) ceramic plate was covered with 100 to 150 mm (4 to 6 in.) of saturated soil (Portneuf silt loam). Eight Watermark sensors were soaked in water overnight and then placed in the soil upright, which is the normal field orientation. The pressure inside the chamber was increased in increments and maintained at each increment for sufficient time to allow resistance readings to stabilize, defined as no change for two consecutive days. The time required for stabilization increased with increased chamber pressure (lower soil water potentials), and ranged from two to three days at 20 kPa (3 psi) to more than two weeks at 103 kPa (14.7 psi). Measurements were made at a temperature of 18° C (64° F) at pressures of 21, 34, 52, and 62 kPa (3, 5, 7.5, and 9 psi). In addition, measurements were made at 14, 18, 22, and 26° C (57, 64, 72, and 79° F) at pressures of 21 and 52 kPa (3 and 7.5 psi). Also, fifty sensors were measured at 20° C (68° F) at pressures of 103 and 150 kPa (15 and 22 psi).

Sensor resistance was measured using the following two devices: 1) a Campbell Scientific Inc. model CR21 data logger, similar to that used by Wang (1988), operated in manual mode; and 2) a Remote Measurements Inc., model SMR-1 resistance measuring circuit.

Resistance measurements from these two devices were compared with measurements from a Beckman impedance bridge and from the circuit used by Thompson and Armstrong (1987), which we constructed and calibrated according to their descriptions. For all the instruments, resistance measurements were checked using standard resistors, and all gave good results within the required range. Also, because an alternating current excitation is used with Watermark sensors, the effect of inductive and capacitive components on total measured sensor impedance was evaluated using an oscilloscope and a variable frequency signal generator. Inductive and capacitive reactances were negligible at the relatively low excitation frequencies used by all the measurement devices. For practical purposes, the Watermark sensors were therefore considered purely resistive transducers.

Dynamic Response

There is no simple way to measure the dynamic response of the sensors independently of the medium in which they are located. Ideally, a step change in soil water potential would be required to evaluate the response time. A reasonable approximation to a step increase in soil water potential is the passage of a wetting front. There is no corresponding approximation to a step decrease in soil water potential, as evaporation and water extraction by plants are much more gradual processes. The change in soil water potential over time behind the wetting front is therefore, more similar to a decay curve than a step function. Comparison with the response of a potentially more rapid instrument, such as a tensiometer, to wetting and drying cycles is one practical method of assessing sensor response time.

The dynamic response of Watermark sensors was measured in a greenhouse, and in the laboratory using a pressure plate apparatus. In the greenhouse, a plastic container approximately 50 cm (20 in.) in diameter and 70 cm (27 in.) in height was filled with field soil (Declo silt loam) and planted with wheat to extract soil water. Various amounts of water were applied from time to time to simulate irrigation. Groups of three Watermark sensors were installed in the soil at depths of 15, 23, 30 and 45 cm (6, 9, 12, and 18 in.). To install the sensors, a pointed rod approximately the same diameter as the sensors was pushed into the soil to the required depth. The resulting hole was then partially filled with water and the sensor directly inserted into it. The hole was then backfilled with soil and lightly tamped.

The sensors were read using an SMR-1 operating through a multiplexer developed at Kimberly for this purpose (Fisher, unpublished data). A thermistor was also installed at each depth to measure soil temperature. A tensiometer equipped with a pressure transducer (Omega, model PX-180-030) was installed at each depth so that it could be logged along with the Watermark sensors. The sensors, tensiometers, and thermistors were read at hourly intervals using a Remote Measurements, Inc. model ADC-1 data logger with a Radio Shack TRS-80 model 102 computer.

Modified Sensors

To evaluate the effect of different transmission matrix materials on dynamic response, some sensors were modified by replacing the transmission section with materials having a higher hydraulic conductivity at lower potentials than the original matrix. The modifications included:

- Replacing the matrix material with gypsum.
- Replacing the matrix material with a kaolin/sand mixture.
- Replacing the entire section with a porous ceramic tip, such as used on tensiometers, filled with gypsum.

Each of the above modifications was made on two sensors. The measurement section was not disturbed, so that the resistance characteristics of the modified sensors would not differ from those of the standard sensors. The static response of the modified sensors was checked in a pressure chamber following the methods described above for standard Watermark sensors. Also in the pressure chamber, the dynamic response of the modified sensors was compared to the response of the standard sensors. Pressure was increased in steps over a period of several days, and the resulting resistance of both modified and standard sensors was measured hourly with a data logger. The water expelled from the pressure chamber was collected in a closed container. Subsequent reductions in chamber pressure caused the expelled water to move back into the soil and rewet it.

Results

Static Response

Figure 2 shows average measured resistance, at 18° C (64° F), at various pressures from 0 to 150 kPa (0 to 22 psi). Also shown are the calibrations from

0 to 100 kPa (0 to 15 psi), of Thomson and Armstrong (1987) and Wang (1988), together with the calibration of the meter supplied by the manufacturer, which reads directly in units of soil water tension (0 to 200 cbar). The meter's calibration was obtained by reading the soil water tension corresponding to various fixed resistance values. In addition, a published calibration for gypsum blocks is shown (Cary, 1981). Figure 2 illustrates the discrepancy between the published calibrations, particularly when the soil is dry. Our resistance measurements were close to the calibration of Wang (1988) (eq. 2). The manufacturer's calibration is linear up to 200 cbar and, up to 100 cbar, is closer to the Thomson and Armstrong (1987) calibration than the Wang (1988) calibration. At pressures higher than 60 kPa (9 psi), we found that resistance measurements did not stabilize within a reasonable time period. Following the initial response, resistance continued to increase slowly over time. At 100 kPa (15 psi), 18 days were required for readings to stabilize. At 150 kPa (22 psi), readings had not stabilized after two months but continued to slowly increase, as shown in figure 2. This slow response at higher pressures contrasts with the findings of Thomson and Armstrong (1987), who reported faster equilibrium times at higher pressures. The effect of temperature on resistance was consistent with both equations 1 and 2 over the measured range.

In the evaluation of sensor variability, one of the fifty sensors tested was rejected because its readings were substantially more than three standard deviations from the mean. The remaining 49 sensors had a mean resistance at 103 kPa (14.7 psi) of 23.1 kΩ, a standard deviation of 2.60 kΩ, and coefficient of variation of 11%. The resulting 95% and 99% confidence intervals on the mean are 22.4 to 23.9 kΩ and 22.1 to 24.1 kΩ, respectively. Table 1 shows, for various confidence levels, the degree of precision with which the above sample mean may be estimated by using the average of various numbers of sensors. Wang (1988) estimated that, at a soil water potential of −103 kPa (−14.7 psi), the average of three sensors would yield an estimate within ± 10% with a 90% confidence level, while from table 1 the number of sensors required would be five to six. For comparison, the cost of three Watermark sensors is

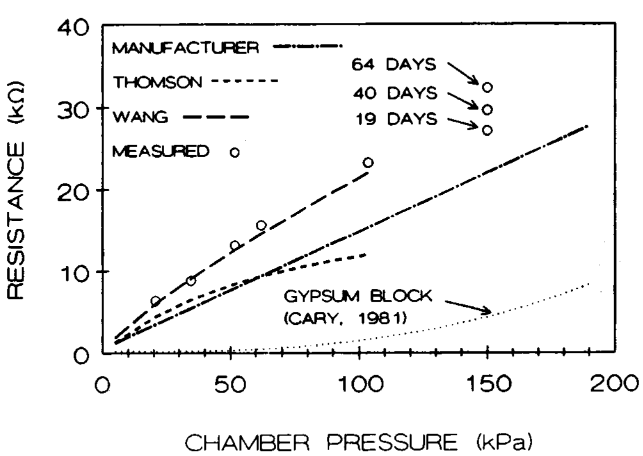

Figure 2–Published calibrations and measured values for Watermark sensor resistance at 18° C (64° F) as a function of soil water potential. Also shown is a gypsum block calibration (Cary, 1981) and the measured resistance at 150 kPa (22 psi) after 19, 40 and 64 days in the pressure chamber.

TABLE 1. Precision with which mean sensor resistance can be estimated (± %), at various confidence levels, by using the average reading from a number of sensors

No. of Sensors	Precision of Measured Average (± % of Mean Sensor Resistance)			
Confidence Level	80%	90%	95%	99%
2	24	50	-	-
3	12	19	28	64
4	9	13	18	33
5	8	11	14	23
6	7	9	12	19

approximately equal to the cost of one tensiometer. The number of sensors required for a particular precision and confidence level is dependent on the coefficient of variation, which in Wang's (1988) study was less than in this study. The difference may be due to the different number of sensors used (12 vs. 49). In the field there is the additional problem of spatial variability of soil water potential, so that there is no certainty, however many sensors are used at a particular location, that they will all be at the same soil water potential.

DYNAMIC RESPONSE

Figure 3a shows a typical mean response of three sensors at 15 cm (6 in.) depth to a series of irrigations (numbered) over a period of time (fig. 3c). Figure 3b shows the corresponding response of the tensiometer at 15 cm (6 in.). Using the tensiometer readings as a measure of soil water potential, both the Watermark sensors and the tensiometer responded to the first irrigation (1), which briefly increased soil water content close to saturation as the wetting front passed. The soil subsequently dried to

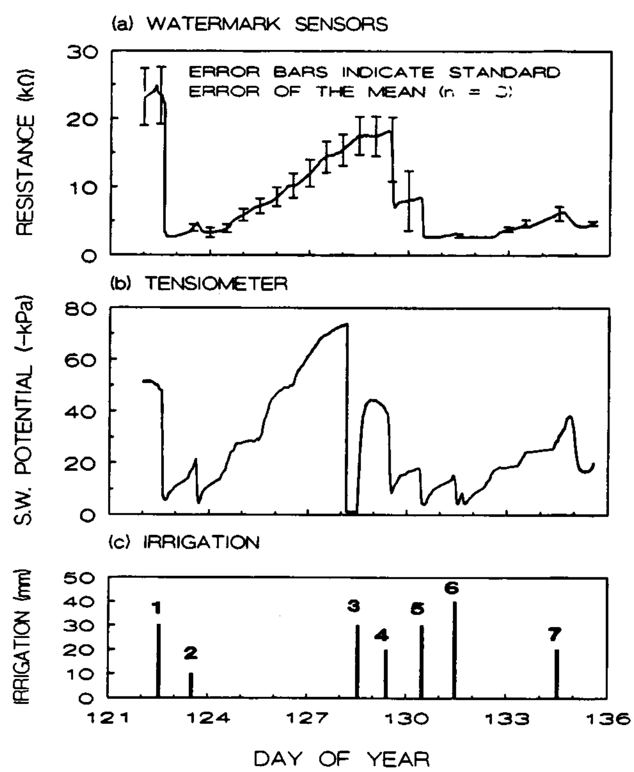

Figure 3–Hourly Watermark (a) and tensiometer (b) response at 150 mm (6 in.) soil depth to a series of irrigations (c).

approximately −21 kPa (−3 psi) before a small irrigation (2) the following day rewetted the soil again. This short wetting and drying cycle was detected by the Watermark sensors. Following this, the soil dried to approximately −70 kPa (−10 psi) over a five day period, towards the end of which the tensiometer began to cavitate, as expected. Prior to this, the tensiometer clearly detected diurnal water extraction and rewetting patterns. In this drying period, during which soil water potential decreased from approximately −3 kPa (−0.4 psi) to −70 kPa (−10 psi), the resistance of the Watermark sensors increased from approximately 3 kΩ to 17 kΩ. The first irrigation at the end of the drying period (3), however, was virtually undetected by the Watermark sensors. Data from the tensiometer were unavailable until the soil had rewetted sufficiently, but it is likely that the irrigation was insufficient to completely rewet the soil. An additional factor is that tensiometers tend to cause a localized increase in soil water content around their tip after resealing. A subsequent irrigation (4) increased potential to approximately −10 kPa (−1.5 psi). The Watermark sensors responded, but their resistance did not decrease to a level consistent with either published calibration and the soil water potential registered by the tensiometer. The next irrigation (5) completely rewetted the soil, enabling sensor resistance to drop to its minimum value, where it remained during the subsequent irrigation (6). Soil water potential then decreased to approximately −40 kPa (−5.8 psi) before the final irrigation (7) partially rewetted the soil. The Watermark sensors during this final phase responded somewhat slower than expected, although there was a response to the final irrigation (7).

Generally, soil water potential in an irrigated environment changes more rapidly closer to the soil surface than it does at greater depths. Figure 4a shows the individual and average readings of three Watermark sensors at 45 cm (18 in.) over a three day period. Figure 4b shows the corresponding tensiometer readings. At 45 cm (18 in.), individual irrigations did not cause the large and rapid changes in soil water potential typical at 15 cm (6 in.). In the ten days prior to the time period in figures 4a and 4b, the three Watermark sensors had a relatively high resistance (20 to 40 kΩ, indicating dry soil), although soil water potential measured with the tensiometer was generally in the −15 to −20 kPa (−2.2 to −2.9 psi) range. A series of irrigations during this period eventually resulted in the slowly increasing soil water potential illustrated in figure 4b. The Watermark sensors, however, did not respond to this gradual increase in soil water content until potential approached approximately −10 kPa (−1.5 psi). The response was then relatively rapid, with resistance falling to its minimum value within a few hours.

It appears that Watermark sensors respond well to soil drying cycles that begin close to saturation. If the soil is not sufficiently wet for long enough to allow the sensors to rewet to their minimum resistance, subsequent resistance readings may be higher than expected. During a wetting cycle, the sensors only respond rapidly and accurately when soil water potentials become high enough to permit sufficient rewetting of the sensor. Soil water potentials greater than approximately −10 kPa (−1.5 psi) seem necessary before the sensors are able to fully rewet. A partial soil rewetting which causes soil water potential to increase but remain less than −10 kPa (−1.5 psi) may either be transparent to the sensor or may reduce response. We have observed a similar response in the field, in which sensors in dry soil do not respond to small irrigations and partial rewetting of the soil profile. The sensors continue to have a high resistance until a large irrigation causes them to resaturate.

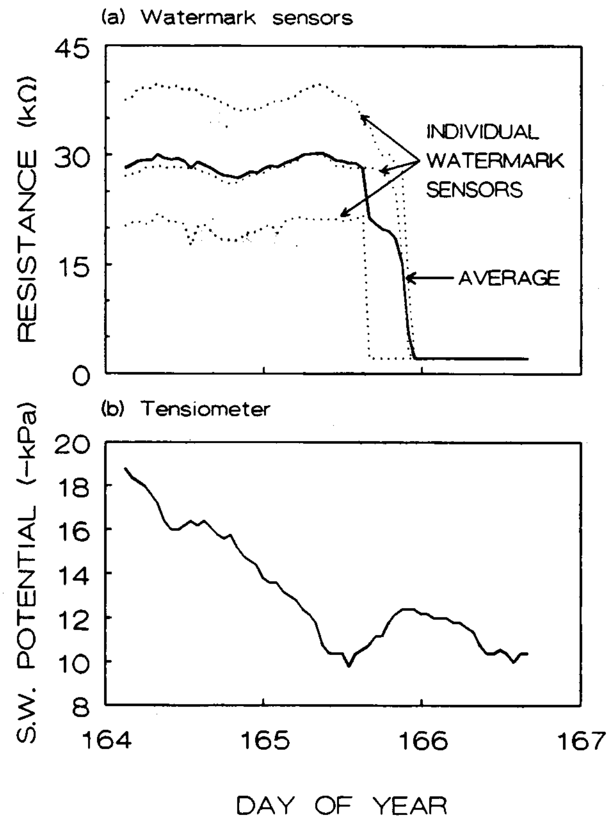

Figure 4–(a) Response of dry Watermark sensors at 450 mm (18 in.) soil depth, (b) to increasing soil water potential measured with a tensiometer.

The slow response at lower soil water potentials, compared with a tensiometer, may be due to low unsaturated hydraulic conductivity in the sensor matrix. In a tensiometer, the wall of the ceramic tip is thin and the pores are filled with water, resulting in a relatively rapid response to changes in soil water potential. Within a Watermark sensor, water must move at a rate governed by the hydraulic conductivity of the matrix and potential gradients within it. The transmission material appears similar to a fine sand, in which hydraulic conductivity at saturation is relatively high but declines rapidly at lower potentials.

Modified Sensors

The static response of the modified sensors in a pressure chamber apparatus confirmed that the modifications to the transmission sections of the sensors had no apparent effect on resistance. Figure 5a shows the dynamic response of the modified sensors to the series of pressure changes illustrated in figure 5b.

The modified sensors all showed a greater response to the step increases in chamber pressure. The individual "steps" to 60 kPa (8.7 psi) can be clearly seen in the modified sensors. The unmodified sensors exhibit a more gradual increase in resistance. Given sufficient time at a particular pressure, the unmodified sensors would likely have had an equilibrium response similar to the modified sensors. The step decrease in pressure from 60 to 20 kPa (8.7 to 2.9 psi) caused a transient decrease in resistance in all the sensors, but it was not until pressure was lowered to 10 kPa (1.5 psi) that a sustained resistance decrease was seen in the modified sensors. Figures 6a and 6b show the results of a similar experiment, in which chamber pressure was increased to 200 kPa (30 psi). After approximately 100 h at 200 kPa (30 psi), the resistances of the modified sensor were nearly stable, and averaged about 34 kΩ. The resistances of the unmodified sensors however were still gradually increasing, and averaged about 18 kΩ.

In both experiments, sensor response was consistent with the previous results, in that resistance values in a wetting cycle did not decline significantly until sufficient time had elapsed and pressure had declined to a sufficiently low value to allow rewetting of the sensor. While actual soil water potential during the pressure decreases was unknown, the differences between the modified and unmodified sensors support the hypothesis that water cannot flow through the standard transmission matrix material rapidly enough under dryer conditions. The matrix material in the measurement section has a similar limitation but, because this section is considerably shorter with resulting shorter flow paths, the effect on sensor response is not as pronounced.

At lower potentials, the response of the sensors is very slow, and equilibrium might require two or more months. The pressure chamber measurements shown in figure 2, after 19, 40, and 64 days, illustrate the gradual increase in resistance over a period greater than two months, at a constant chamber pressure of 150 kPa (22 psi). Figure 6 also illustrates the slow response of the standard sensors at a chamber pressure of 200 kPa (30 psi).

Discussion

The reason for the discrepancy between the Thomson and Armstrong (1987) calibration and the Wang (1988) calibration is not clear. One explanation is that the design of the sensors has been modified over time, so that the sensors we (and Wang) used had a different static response than the sensors used by Thomson and Armstrong. Certainly, the sensors used by Thomson and Armstrong were manufactured by the Larsen company, while the sensors we used were manufactured by the Irrometer company, who had by then acquired the design from the Larsen company. The Irrometer company indicates (personal communication) that other unpublished research shows that the current model (which we used) may well have an equilibrium resistance of 40 kΩ at a soil water potential of −200 kPa (−30 psi). Neither the Wang nor the Thompson and Armstrong equations were developed for soil water potentials less than −100 kPa (−15 psi). However, if these equations are extrapolated past their intended range to −200 kPa (−30 psi), they yield resistance estimates of approximately 36 kΩ and 15 kΩ, respectively, at a temperature of 18° C (64° F).

The dynamic response of Watermark sensors appears to be good down to about −50 kPa (−7.3 psi) during a drying cycle, if the sensors are initially and completely rewetted. Below this potential, the transmission material may not be able to conduct water sufficiently rapidly to maintain equilibrium with the soil water. One potential problem this poses for irrigation scheduling is that under certain conditions, the sensors may be slow to detect water stress.

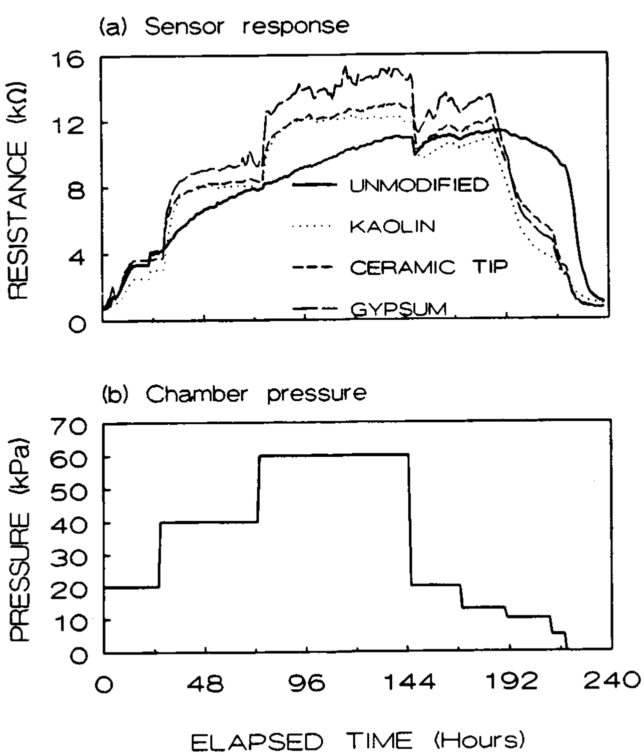

Figure 5–Response of standard and modified Watermark sensors (a) to changes in chamber pressure (b) over time. Maximum chamber pressure was 60 kPa (9 psi).

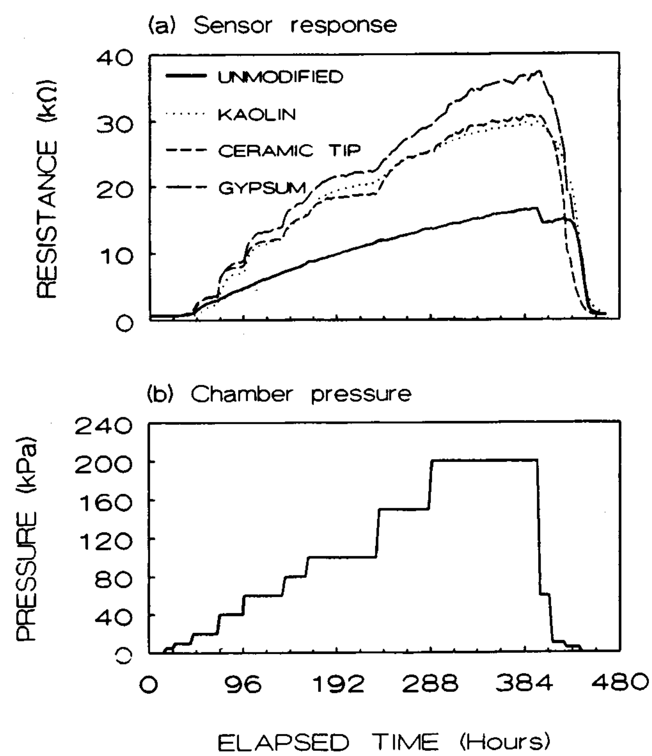

Figure 6–Response of standard and modified Watermark sensors (a) to changes in chamber pressure (b) over time. Maximum chamber pressure was 200 kPa (30 psi)

This could happen, for example, during periods of high evaporative demand if the soil water depletion rate were greater than the response rate of the sensors. The problem would be magnified in soils with low available water holding capacities and in crops with shallow root zones. Under these conditions, however, it is poor management practice to let soil water potential decrease to −50 kPa (−7.3 psi).

On the other hand, there are conditions under which the slow sensor response to rewetting could present a problem. For example, sensors at the bottom of the root zone may not completely respond to partial rewetting, even though the soil near the sensor is close to field capacity. The sensor may therefore indicate further irrigation is required even though much of the additional water may percolate out of the root zone and add no value to the crop.

Where irrigation amounts are typically relatively large, such as with surface or stationary sprinkler systems, much of the root zone is replenished and the sensors may respond well to the soil drying between irrigations. However, where irrigation amounts tend to be small, such as with center-pivot irrigation, soil water potential in the bulk of the root zone may not increase sufficiently to completely rewet the sensors. In this case, at least some sensors should be located relatively close to the surface, where the small irrigations may increase the soil water potential sufficiently to cause an adequate response. Additional sensors located closer to the bottom of the root zone may then also be required. These lower sensors could be used to detect when soil water potential is greater than the approximately −10 kPa rewetting threshold. If soil water potential is high enough to rewet the sensors, then readings during the subsequent drying cycle should be accurate. If, however, the sensors have not been completely rewetted, subsequent readings may not be useful. To rewet the sensors however, soil water content near the bottom of the root zone likely needs to be at or above field capacity, with the possibility that subsequent irrigations may result in excessive soil water content and downward water movement.

Summary and Conclusion

Watermark Model 200 sensors have a potential use in irrigation management where soil near the sensor is sure to be resaturated during typical irrigations. They appear to respond satisfactorily to drying cycles in the soil, provided they begin the cycle fully rewetted. The response to partial soil rewetting is slow or non-existent. Unless soil water potential exceeds approximately −10 kPa (−1.5 psi), the movement of water into the sensor may not be sufficiently rapid to allow it to respond to subsequent soil drying. Thus, the sensors should be situated within the soil profile at a depth where irrigations cause soil water potential to exceed this threshold. Modifying the transmission section of the sensors to increase hydraulic conductivity at typical root zone soil water potentials improved the sensor's dynamic response. Using multiple sensors at a location may improve the accuracy of soil water content estimations. A reasonable compromise between cost, convenience and accuracy might be to have three to six sensors at a given location and depth and to use their average in determining soil water content.

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